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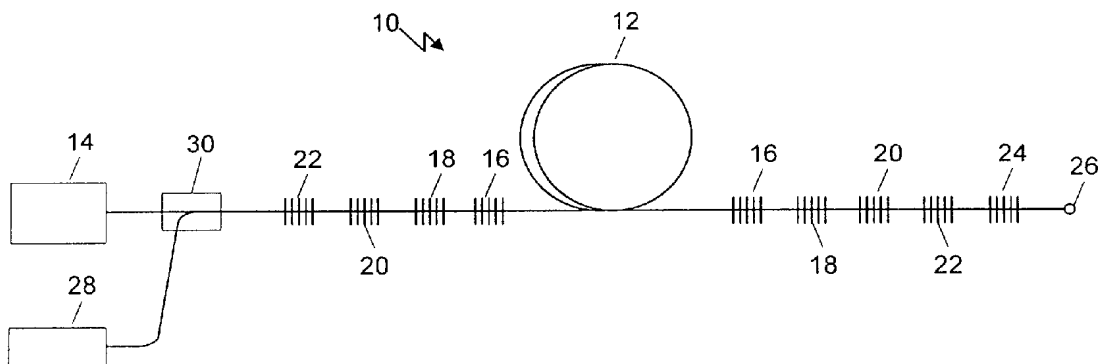
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(54) Title: CASCADED RAMAN RESONATOR WITH GAIN PROFILE SEEDING



(57) Abstract: A signal source has a cascaded Raman resonator type arrangement with a seed signal being used to control the spectral output of the source. A plurality of Stokes orders are generated in a gain medium, with the highest Stokes order being allowed to exit. The seed signal is provided to the gain medium by a seed source, and is within the wavelength range of the highest Stokes order. The seed signal stimulates Raman-shifted gain in the wavelength range of the seed signal, thereby allowing the output wavelength range of the gain medium to be controlled. In one embodiment, the seed signal is a broadband signal that results in a broadband output from the gain medium. In another embodiment, the seed signal is provided by a number of narrowband sources coupled together before being introduced to the gain medium. The seed source may be adjusted to adjust the spectral power distribution of the output from the signal source. Adjustment may be done in combination with active signal monitoring of the signal source output. Alternatively, the signal source may be used to pump a gain medium in which a desired signal is amplified, and the spectral power distribution of the desired signal may be monitored for making seed source adjustments.



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## CASCADED RAMAN RESONATOR WITH GAIN PROFILE SEEDING

### FIELD OF THE INVENTION

This invention relates generally to optical gain devices and, more specifically, to optical gain devices using stimulated Raman scattering in a cascaded wavelength-shifted arrangement.

### BACKGROUND OF THE INVENTION

An optical gain medium is a device that, when provided with optical pumping energy, increases the amplitude of a desired optical signal. Optical gain media may be constructed using optical fiber, and used for fiber lasers or fiber-based optical amplifiers. One form of optical amplifier known in the art is based on stimulated Raman scattering (SRS), and is referred to generally as a "Raman amplifier." In a Raman amplifier, optical pumping energy is injected into an optical fiber medium through which the signal to be amplified is conducted. The optical pumping energy, via SRS, allows for a transfer of optical power to a wavelength longer than the pumping wavelength, due to the excitation of a vibrational mode in the medium that provides gain at the longer wavelength. A Raman laser is similar, but has no signal to be amplified, and through SRS, simply develops the pump signal into an output signal of higher power and longer wavelength using a resonator structure.

The longer wavelengths to which optical power is transferred in a Raman gain medium may be predetermined relative to the wavelength of the pumping energy. These wavelength shifts are referred to as "Stokes" shifts and, since each Stokes shift is a known amount relative to the wavelength from which the energy is transferred, a resulting "Raman-shifted" wavelength may be selected by proper selection of the pumping wavelength. In one particular type of Raman gain medium, overlapping resonant cavities are constructed for a number of progressively longer Raman-shifted wavelengths all based on the same initial pumping wavelength. That is, the shifted wavelength resulting from the pumping wavelength, referred to as the "first Stokes order" is resonated within the gain medium, generating its own shifted wavelength that is a predetermined amount longer than the first order wavelength. This "second order" wavelength is, in turn, resonated within the cavity to generate a "third Stokes order" wavelength. By accurate selection of the different resonant reflectors and the initial pumping wavelength, a number of Stokes shifts may be used to generate an optical signal at a desired output wavelength significantly longer than the pumping

wavelength. This type of optical device is generally referred to as a "cascaded Raman resonator," and an example of such a device is described in U.S. Pat. No. 5,323,404.

A cascaded Raman resonator (CRR) is a useful device for providing Raman amplification at a target wavelength while pumping at a shorter wavelength. For example, in a typical CRR, a pumping wavelength of 1117 nm might be used to generate a target wavelength of 1480 nm by providing resonant cavity reflectors for the intermediate Stokes order wavelengths of 1175 nm, 1240 nm, 1311 nm and 1391 nm. However, while a desired output wavelength may be produced in this manner, it would be desirable to have a CRR with additional advantages such as a wider gain bandwidth at high powers in order to reduce the occurrence of stimulated Brillouin scattering (SBS) found in prior art CRR devices.

#### **SUMMARY OF THE INVENTION**

In accordance with the present invention, an optical signal source is provided that has a high power output across a relatively wide bandwidth. The signal source has an optical gain medium that is suitable for generating gain via SRS, that is, it provides optical gain at a plurality of Raman-shifted wavelengths in response to optical pump energy having a pump wavelength shorter than the shifted wavelengths. A pump source supplies optical energy at the pump wavelength to the gain medium, and a plurality of reflectors are provided to create a resonant cavity through the gain medium. In particular, the reflectors may be narrowband reflectors arranged in a CRR type configuration, such that optical energy passing through the gain medium is progressively shifted to longer wavelengths, stepping from the pump wavelength through several Stokes orders up to a desired output wavelength. The reflectors are such that each of the intermediate wavelengths is resonated through the gain medium except for the output wavelength, which is allowed to exit.

The resonating intermediate wavelengths cause gain at the resulting Raman-shifted wavelengths. However, the particular wavelength ranges at which the SRS gain is realized are controlled by supplying optical "seed" energy to the gain medium. An optical seed source is provided that couples optical energy in the output wavelength range into the gain medium. For a given Stokes orders, gain can result anywhere within a range of SRS wavelengths. The seed energy in the output wavelength range stimulates gain within that range at the desired output wavelengths. For example, the seed energy may be broadband energy that stimulates SRS gain at

all wavelengths across a relatively wide portion of the output wavelength range. In this way, a high power, broadband signal is generated. The signal source may be combined with a subsequent gain medium, such as a transmission line capable of providing SRS gain. The signal source can function as a pump source for the gain medium, providing it with high power, broadband pump energy that provides signal gain to an optical signal on the transmission line across a relatively wide bandwidth.

In another embodiment of the invention, the signal source is again based on a gain medium that provides Raman-shifted gain, and that uses a seed source to control the wavelengths output by the signal source. However, in this embodiment, the seed source consists of a number of different narrow bandwidth optical sources that are coupled together before being coupled into the gain medium. The separate sources are each independently controllable, and allow the relative seed powers at the different wavelengths to be adjusted. This, in turn, affects the relative power in different wavelength ranges output by the signal source.

Like the broadband seed source embodiment, the multiple narrowband seed source embodiment may be used to pump a subsequent gain medium. Active control of the seed sources may also be used, and a feedback path provided that adjusts the power of each of the sources in response to the spectral power distribution in a signal on the gain medium being pumped by the signal source. For example, a signal on a transmission line being pumped by the signal source to provide Raman gain may be monitored, and the spectral power distribution of the seed source output adjusted in response. The adjustment may be such that the gain provided by the transmission line tends to balance the spectral power distribution of the signal on the transmission line.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the invention may be better understood by referring to the following description in conjunction with the accompanying drawings in which:

FIG. 1 depicts a first embodiment of the invention in which a seeded CRR signal source has a broadband seed source;

FIG. 2 depicts a second embodiment of the invention in which a seeded CRR signal source has a seed source consisting of a number of separate narrow bandwidth sources coupled together; and

FIG. 3 depicts an application of the signal source in which a transmission line is pumped for SRS gain, and a signal on the transmission line is monitored for use in making active adjustments to the seed source output.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Shown in FIG. 1 is a first embodiment of a signal source 10 in which a CRR is used in a manner that allows the generation of a desired output signal, one that has a desired wavelength profile. Amplification is done in a gain medium 12 that is particularly suited for generating gain via SRS. One type of gain medium that would be useful is a single mode fiber that is highly doped with germanium ( $\text{Ge}^{3+}$ ), and that is of relatively long length (e.g., 500-1000 meters long). However, other Raman gain media are also known in the art, and are considered to be equivalents for the purpose of the invention. An initial pump signal for the CRR is provided by a pump source 14. One type of pump source that might be used with the invention is a cladding pumped fiber laser, which itself might be pumped by a diode laser or other light source. However, those skilled in the art will recognize that other equivalents exist that may be used for the pump source 14.

As an example, the pump source 14 may generate an output signal with a center wavelength of 1100 nm. A reflector 24 is highly reflective at the pump wavelength, and reflects pump energy escaping the gain medium 12 back into it. A first pair of reflectors 16 (diffraction gratings in the preferred embodiment) is provided, each reflector being highly reflective in a narrow wavelength band centered about, e.g., 1156 nm. As pump energy is converted to a longer wavelength range by SRS, a resonant condition develops through the gain medium 12 for optical energy around 1156 nm wavelength, which represents a first Stokes shift relative to the pump wavelength. Another pair of gratings 18 having a reflectivity band centered around, e.g., 1218 nm resonates optical energy in the fiber 12 that has been shifted by SRS from the 1156 nm wavelength range to the 1218 nm wavelength range. The 1218 nm optical energy range therefore represents a second Stokes shift relative to the pump energy. This resonating optical energy, in turn, produces a third Stokes order, which is reflected by grating pair 20, each grating of which has a center reflectivity wavelength of, e.g., 1286 nm. Finally, grating pair 22 provides a resonant condition for a fourth Stokes order, having a center reflectivity wavelength of, e.g., 1363 nm.

The resonance of the fourth Stokes order causes the generation of optical energy in the gain medium 12 at a fifth Stokes order due to SRS. There is no grating

pair in the embodiment to resonate this fifth order within the gain medium, and it therefore escapes to output port 26. However, the optical energy generated in this wavelength band by the gain medium is controlled both as to wavelength and effective bandwidth by the introduction of optical energy to the gain medium from seed source 28.

Seed source 28 provides a predetermined optical signal that is coupled into to the gain medium 12 via optical coupler 30, which may be, for example, a wavelength division multiplexer (WDM). The optical signal from seed source 28 is referred to as a "seed" signal, because it promotes generation of Raman-shifted optical energy (*i.e.*, SRS gain) in the gain medium 12 at the wavelength of the seed signal. That is, there is a predominant development of optical power at the wavelengths of the seed signal. This allows for a great deal of control over the output of the CRR structure shown. For example, if the seed signal has a relatively broad wavelength band, so will the fifth Stokes order signal reaching output port 26. Examples of such broadband seed sources include, but are not limited to, a Fabry-Perot laser diode, a grating stabilized diode in coherence-collapse, an LED, or an ASE source.

An alternative embodiment of the invention is shown in FIG. 2, which uses the same components as FIG. 1, but has a different seed source. Instead of using a single broadband seed source, the signal source 11 of FIG. 2 uses a signal combined from a number of individual narrowband optical sources. Optical sources 32, 34, 36 and 38 each output optical energy at a different wavelength. In the preferred embodiment, the wavelength ranges of the sources are closely spaced together, and may overlap. For example, the sources 32, 34, 36 38 may have center wavelengths, respectively, of 1445 nm, 1450 nm, 1455 nm and 1460 nm. The optical energy from the sources 32, 34, 36, 38 is combined together using an array of narrowband couplers, such as narrowband WDMs 40, 42, 44. This combined signal is then coupled into the gain medium 12 via optical coupler 30.

As each of the wavelength ranges of the sources 32, 34, 36, 38 is within the range of the fifth Stokes order, each produces optical power in its wavelength band via SRS. Thus, the output of the signal source of FIG. 2 is a high-power broadband/multiple wavelength band signal. However, since a number of different individual seed sources 32, 34, 36, 38 are used, the input powers of each may be adjusted to control the amount of SRS gain, and therefore the output power, in each of the bands. This enables an initial power balancing adjustment to be done. As

discussed below, a feedback mechanism may also be implemented that adjusts the relative powers of the different sources in response to monitoring of the output signal of the signal source 11, or the monitoring of a subsequent device.

Four different seed sources 32, 34, 36, 38 are used in the embodiment of FIG.

2. However, those skilled in the art will recognize that any number of different seed sources may be combined together as desired. Moreover, a single broadband source may be combined with narrow wavelength band sources as desired to provide a similar adjustable seeded signal source. The invention also need not be used to pump a subsequent amplifier. Numerous other uses will be recognized, and are considered to be within the scope of the invention.

One particular use for either of signal sources 10, 11 shown in FIGS. 1 and 2 is as an optical source for certain applications. For example, the source may be used to pump a Raman gain medium, such as transmission fiber 50, shown in FIG. 3. The signal source 10, 11 provides a high power broadband or multiple wavelength optical signal that is coupled into the transmission fiber 50 via a coupler 52, which may be, e.g., a WDM. The transmission fiber, while being a low loss medium for the signal wavelength, will also provide gain at the signal wavelength via SRS when pumped with a pump signal having the appropriate wavelength range. For example, if the transmission fiber carries an optical signal in the wavelength range of 1550 nm, a pump signal coupled into the fiber in the wavelength range of 1450 nm can result in Raman gain in the signal wavelength range. Thus, the signal output from either of the signal sources 10, 11 is suitable for this purpose. Moreover, the high power, broadband signals output from these sources provide high power pumping of the amplifier across a relatively wide gain bandwidth, and an optical signal on the transmission fiber 50 is provided with amplification over a relatively wide wavelength band. This allows for amplification of a higher number of signal channels than would be available using a conventional pump source. The seed sources may also be controlled so that the SRS gain being provided by the fiber 50 has a desired degree of gain flatness.

Also shown in FIG. 3 is an automatic control module 54. This module may be used to provide active control of the source 10, 11 in response to a monitoring of the optical signal on the transmission line. In the figure, the controller 54 is shown having a signal input from a point 56 on the transmission line, which may be, for example, a repeater node. This point may or may not be in the range of the pump signal provided

by the source 10, 11. That is, the monitored point may be located at a position for which amplification by the signal from the source 10, 11 has already taken place, or it may be located at a position far enough away from the source 10, 11 that the optical signal has not yet encountered the Raman gain provided by the source signal.

5 Alternatively, the controller 54 may simply monitor the pump signal output by the signal source. Those skilled in the art will also recognize that the communication between the controller 54 and the monitored point, and between the controller 54 and the 10,11 may be provided in any known manner, including wireless communication.

Whether or not the monitored signal has yet been amplified by the Raman gain  
10 provided by the signal source 10,11, information is collected as to which wavelength ranges of the transmitted signal have degraded more than others. This information is used by controller 54 to modify the wavelengths output by the seed sources of the signal source 10, 11. In the case of the single broadband seed source of the FIG. 1, control may be provided that allows a shifting of the power in the output wavelength  
15 range of the seed source toward seed wavelengths that induce more gain at the wavelengths for which the transmitted optical signal is more depleted. Similarly, the information may be used to control the seed sources so that the SRS gain being provided by the fiber 50 has a desired degree of overall gain flatness. For the discrete optical sources of the FIG. 2 seed source, each may be individually adjusted by the  
20 controller so that the desired range of pumping powers are provided. In this way, active control of the source 10, 11 allows the SRS gain from fiber 50 to be provided in any of a variety of desired ways.

While the invention has been shown and described with regard to preferred  
embodiments thereof, it will be recognized by those skilled in the art that various  
25 changes in form and detail may be made herein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:



## CLAIMS

- 1 1. An optical signal source comprising:  
2 an optical gain medium that provides optical gain at a plurality of Raman-  
3 shifted wavelengths in response to optical pump energy in a pump wavelength  
4 range;  
5 an optical pump source that couples optical energy into the gain medium  
6 in the pump wavelength range;  
7 a plurality of reflectors located to either side of the gain medium that  
8 create a resonant cavity through the gain medium for at least one of the  
9 Raman-shifted wavelengths, while allowing optical energy in an output  
10 wavelength range to exit the gain medium; and  
11 an optical seed source that couples optical energy in the output  
12 wavelength range into the gain medium.
- 1 2. An optical signal source according to Claim 1 wherein the signal source  
2 comprises a cascaded Raman resonator.
- 1 3. An optical signal source according to Claim 1 wherein the Raman-shifted  
2 wavelengths comprise Stokes orders relative to the pump wavelength range.
- 1 4. An optical signal source according to Claim 1 wherein the reflectors comprise  
2 diffraction gratings.
- 1 5. An optical signal source according to Claim 1 wherein the seed source  
2 comprises a broadband optical source.
- 1 6. An optical signal source according to Claim 1 wherein the seed source  
2 comprises a plurality of separate optical sources coupled together, the separate  
3 optical sources having different wavelength ranges.
- 1 7. An optical signal source according to Claim 6 wherein the separate optical  
2 sources are coupled together via at least one wavelength division multiplexer.

- 1 8. An optical signal source according to Claim 6 wherein the separate optical  
2 sources are each independently controllable in power output.
- 1 9. An optical amplifier comprising:  
2 an amplifier optical gain medium that provides optical gain to an input  
3 signal in response to optical source energy in a first wavelength range; and  
4 a signal source that provides optical energy in the first wavelength range  
5 to the amplifier gain medium, the signal source comprising:  
6 a pump optical gain medium that provides optical gain at a  
7 plurality of Raman-shifted wavelengths in response to optical pump  
8 energy in a pump wavelength range;  
9 an optical pump source that couples optical energy into the pump  
10 gain medium in the pump wavelength range;  
11 a plurality of reflectors located to either side of the pump gain  
12 medium that create a resonant cavity through the pump gain medium for  
13 at least one of the Raman-shifted wavelengths, while allowing optical  
14 energy in the first wavelength range to be coupled out of the pump gain  
15 medium; and  
16 an optical seed source that couples optical energy in the first  
17 wavelength range into the gain medium.
- 1 10. An optical amplifier according to Claim 9 wherein the signal source comprises a  
2 cascaded Raman resonator.
- 1 11. An optical amplifier according to Claim 9 wherein the Raman-shifted  
2 wavelengths comprise Stokes orders relative to the pump wavelength range.
- 1 12. An optical amplifier according to Claim 9 wherein the reflectors comprise  
2 diffraction gratings.
- 1 13. An optical amplifier according to Claim 9 wherein the seed source comprises a  
2 broadband optical source.

- 1 14. An optical amplifier according to Claim 9 wherein the seed source comprises a  
2 plurality of separate optical sources coupled together, the separate optical  
3 sources having different wavelength ranges.
- 1 15. An optical amplifier according to Claim 14 wherein the separate optical sources  
2 are coupled together via at least one wavelength division multiplexer.
- 1 16. An optical amplifier according to Claim 14 wherein the separate optical sources  
2 are each independently controllable in power output.
- 1 17. An optical amplifier according to Claim 9 further comprising a controller that  
2 monitors the input signal and adjusts the seed source in response thereto.
- 1 18. An optical amplifier according to Claim 17 wherein the controller adjusts the  
2 seed source in a manner that tends to balance a spectral power distribution of  
3 the input signal.
- 1 19. A method of generating an optical signal, the method comprising:  
2 providing an optical gain medium that provides optical gain at a plurality  
3 of Raman-shifted wavelengths in response to optical pump energy in a pump  
4 wavelength range;  
5 coupling optical energy into the gain medium in the pump wavelength  
6 range;  
7 developing a resonant condition within the gain medium for at least one  
8 of the Raman-shifted wavelengths, while allowing optical energy in an output  
9 wavelength range to exit the gain medium; and  
10 coupling optical energy in the output wavelength range into the gain  
11 medium with an optical seed source.
- 1 20. A method according to Claim 19 wherein the signal source comprises a  
2 cascaded Raman resonator.
- 1 21. A method according to Claim 19 wherein the Raman-shifted wavelengths  
2 comprise Stokes orders relative to the pump wavelength range.

- 1 22. A method according to Claim 19 wherein the resonant condition in the gain  
2 medium is developed using reflectors positioned to either side of it.
- 1 23. A method according to Claim 19 wherein coupling optical energy in the output  
2 wavelength range into the gain medium with a seed source comprises coupling  
3 broadband optical energy into the gain medium.
- 1 24. A method according to Claim 19 wherein the seed source comprises a plurality  
2 of separate optical sources coupled together, the separate optical sources  
3 having different wavelength ranges.
- 1 25. A method according to Claim 24 wherein the separate optical sources are  
2 coupled together via at least one wavelength division multiplexer.
- 1 26. A method according to Claim 24 wherein the separate optical sources are each  
2 independently controllable in power output.
- 1 27. A method of amplifying an optical input signal, the method comprising:  
2 providing an amplifier optical gain medium that provides optical gain to  
3 the input signal in response to optical source energy in a first wavelength  
4 range; and  
5 coupling optical energy in the first wavelength range to the amplifier gain  
6 medium with a signal source comprising:  
7 a pump optical gain medium that provides optical gain at a  
8 plurality of Raman-shifted wavelengths in response to optical pump  
9 energy in a pump wavelength range;  
10 an optical pump source that couples optical energy in the pump  
11 wavelength range into the pump gain medium;  
12 a plurality of reflectors located to either side of the pump gain  
13 medium that create a resonant cavity through the pump gain medium for  
14 at least one of the intermediate wavelengths, while allowing optical  
15 energy in the first wavelength range to be coupled out of the pump gain  
16 medium; and

17                            an optical seed source that couples optical energy in the first  
18                            wavelength range into the gain medium.

1    28.    A method according to Claim 27 wherein the signal source comprises a  
2           cascaded Raman resonator.

1    29.    A method according to Claim 27 wherein the Raman-shifted wavelengths  
2           comprise Stokes orders relative to the pump wavelength.

1    30.    A method according to Claim 27 wherein the reflectors comprise diffraction  
2           gratings.

1    31.    A method according to Claim 27 wherein the seed source comprises a  
2           broadband optical source.

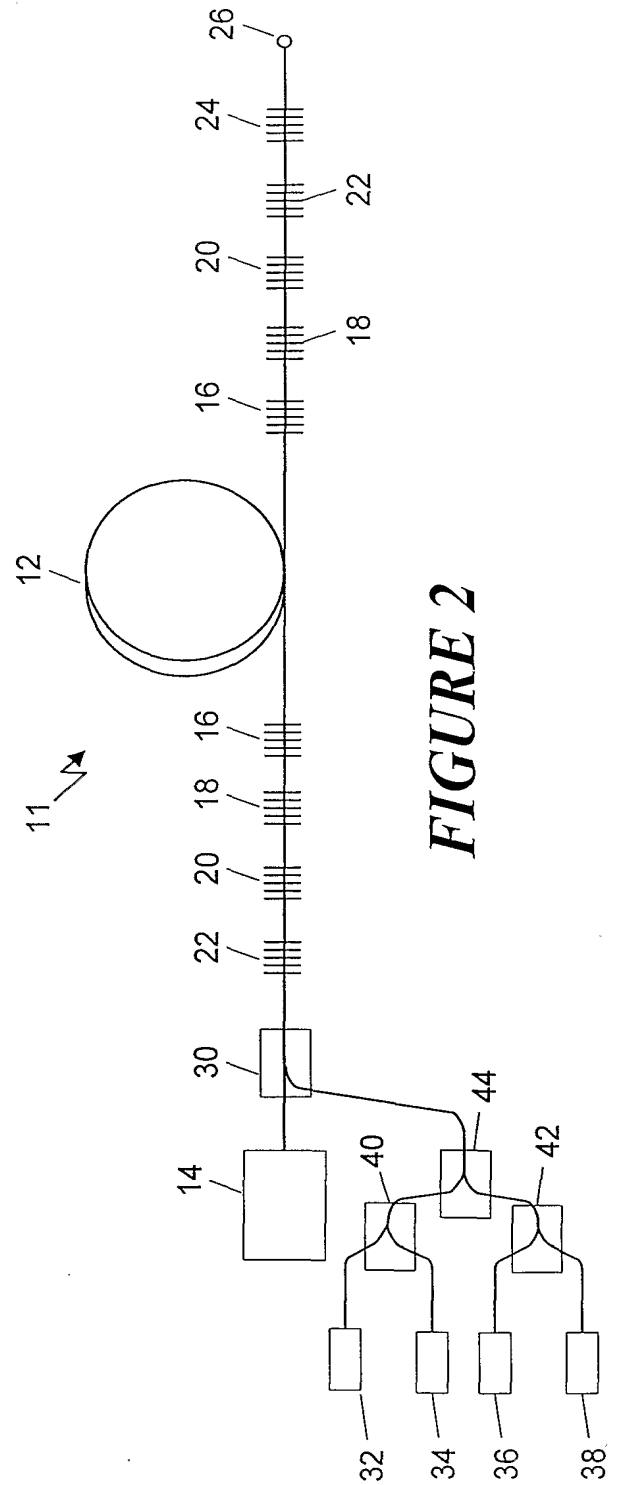
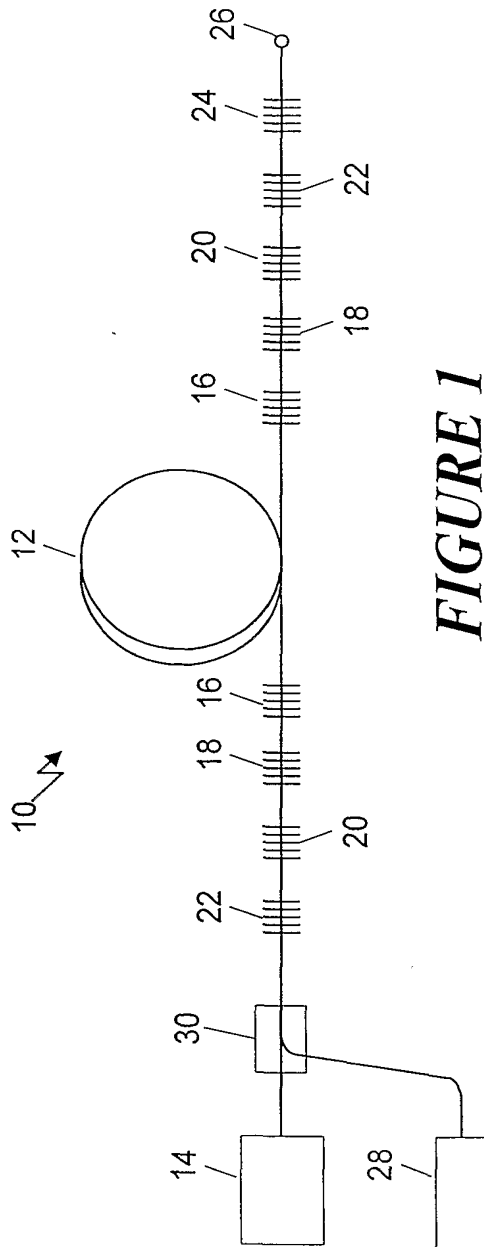
1    32.    A method according to Claim 27 wherein the seed source comprises a plurality  
2           of separate optical sources coupled together, the separate optical sources  
3           having different wavelength ranges.

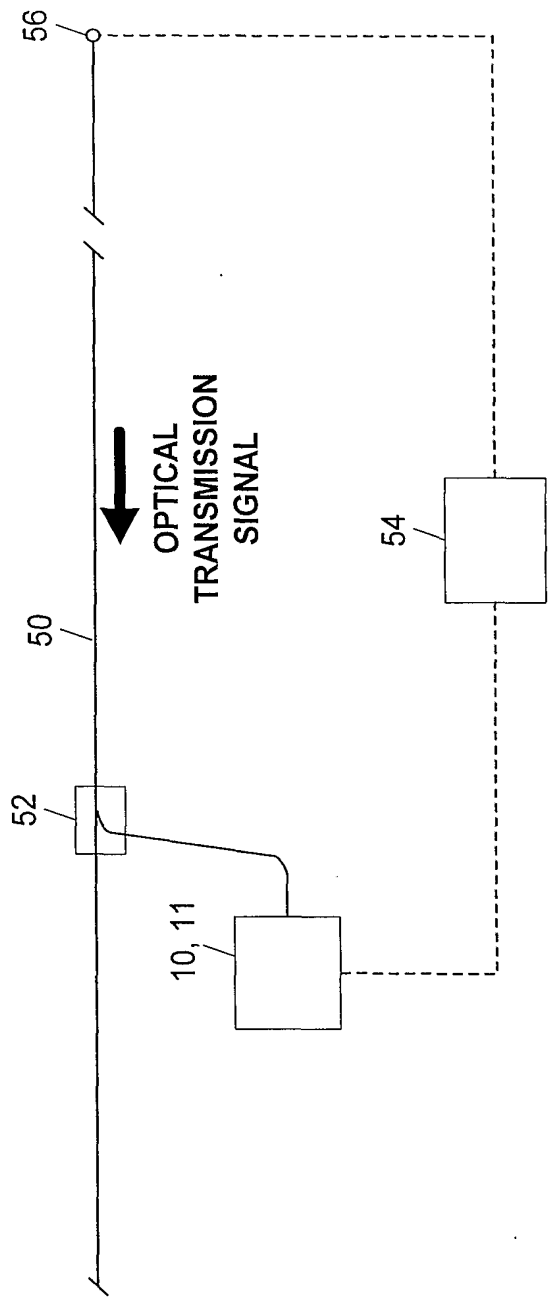
1    33.    A method according to Claim 32 wherein the separate optical sources are  
2           coupled together via at least one wavelength division multiplexer.

1    34.    A method according to Claim 27 wherein the separate optical sources are each  
2           independently controllable in power output.

1    35.    A method according to Claim 27 further comprising monitoring the input signal  
2           and adjusting the seed source in response thereto.

1    36.    A method according to Claim 35 further comprising adjusting the seed source in  
2           a manner that tends to balance a spectral power distribution of the input signal.





*FIGURE 3*